

# Quasars and Jet Sources

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A class of active galactic nuclei show radio jets that are presumably formed by a supermassive black hole engine. A review of quasar discovery and properties is presented.

# The Discovery of Quasars

The extraordinary nature of the quasi-stellar objects (or quasars as they came to be called) was not apparent when they were first cataloged in radio surveys in the 1950's. It was only after the angular size of some of these sources was investigated that they appeared as a distinct phenomenon. In the Third Cambridge (3C) Catalog of radio sources, published in 1960, the average size of the sources was 30 seconds of arc. However a small group of sources was found to have sizes less than the resolution of the radio telescope (one second of arc) used in the survey. With the position defined to this accuracy it was easy to optically identify some of these sources. Four of these objects: 3C 48, 3C 147, 3C 196 and 3C 286 were tentatively identified with optical objects on photographic plates which appeared to be stellar, rather than galactic, in scale.

The existence of "radio stars" had been considered in the early stages of the development of radio astronomy. When it was realized that the radio emission from the sun was very weak in absolute terms, the concept fell into disfavor. Most of the radio sources in the sky were radio galaxies or supernovae remnants. The suggestion that these four objects were "radio stars" reopened the debate of whether there could be significant emission from stars. Although emission lines were seen in the spectra of these objects they did not correspond to any known elements.

# The Discovery of Quasars

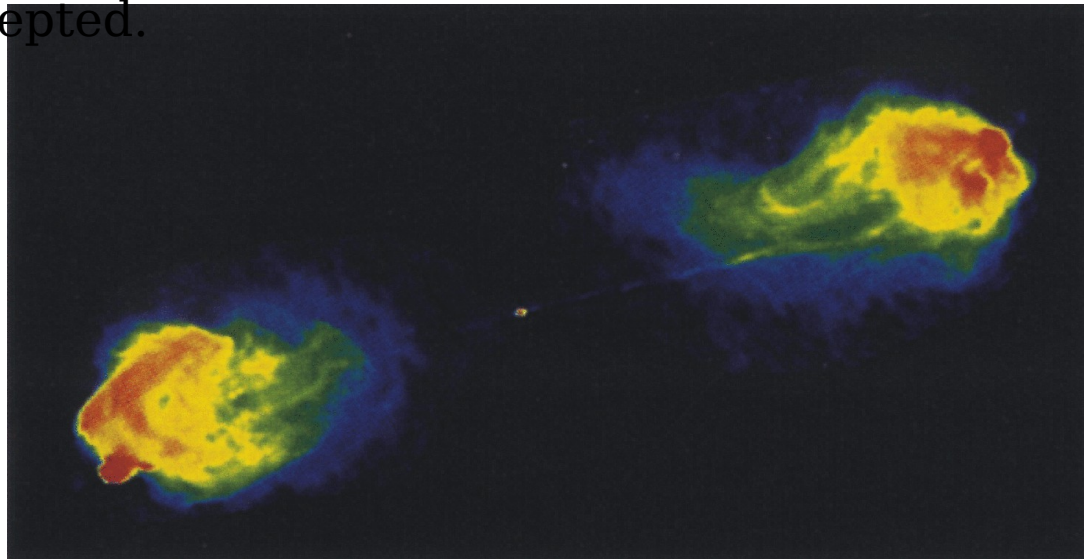
## (continued, part 2)

A group of Australian radio astronomers used the lunar occultation method to determine the position and structure of 3C 273, one of the unidentified objects in the 3C Catalog. The radio source was known to be double and the new observations showed that the radio sources coincided with a star-like object and a nearby jet. Martin Schmidt measured the spectrum of the star-like object and found that they had six emission lines; four of them had a pattern which suggested that they might come from the same element. But no element was known with these emission lines. Schmidt realized that if the lines were redshifted then they would correspond to emission from hydrogen. However the redshift was large ( $z=0.16$ ). The other two lines could then be identified with magnesium and oxygen.

Greenstein and Matthews then realized that the spectral lines from 3C 48 could also be identified if a redshift of  $z = 0.37$  was assumed. The spectra of the other objects could be explained similarly. Hence the "radio stars" were extragalactic and extremely bright. From examination of old photographic plates variations of times scales of years were apparent, implying very small sizes. Quasars were thus the brightest objects in the universe and the long controversy as to the source of the energy was born.

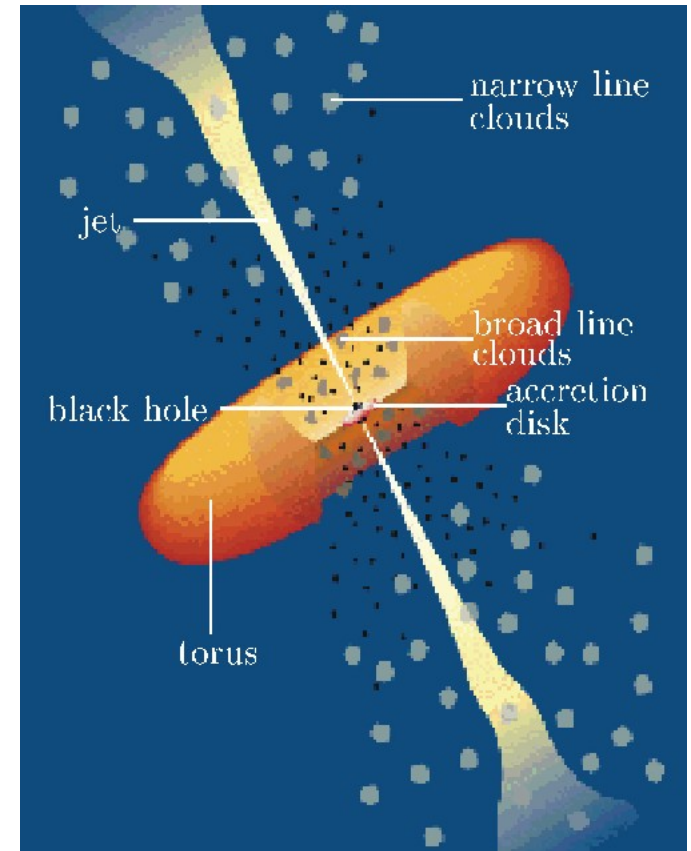
# The Discovery of Quasars, part 3

The problem of explaining the enormous power radiated from extra-galactic radio galaxies was compounded in quasars by the need to explain emission in the visible bands also and to extract it from a very small object. If the quasars only lasted a short time, then the problem would not be so great. However the length of the jet in 3C 273 suggested that it had been expelled 100,000 years ago! It took some time before the canonical theory of quasars, that they consist of massive black holes, was accepted.



# Active Galactic Nuclei

Active galactic nuclei (AGN) contain a compact central source which is widely believed to be a black hole of  $10^6$  to  $10^9$  solar masses. Its gravitational potential energy is the power source for the AGN emission. Surrounding the black hole is an accretion disk of matter which glows brightly at ultraviolet (UV) wavelengths, and perhaps soft X-rays. Clouds of gas moving at high speeds around the central core produce strong, broad optical and UV emission lines. These clouds in turn are surrounded by a torus or warped disk of gas and dust which obscures optical and UV radiation. Outside the torus, slower moving clouds of gas produce narrow emission lines. In some AGN, highly relativistic outflows of energetic particles form collimated radio-emitting jets with axes perpendicular to the plane of the accretion disk

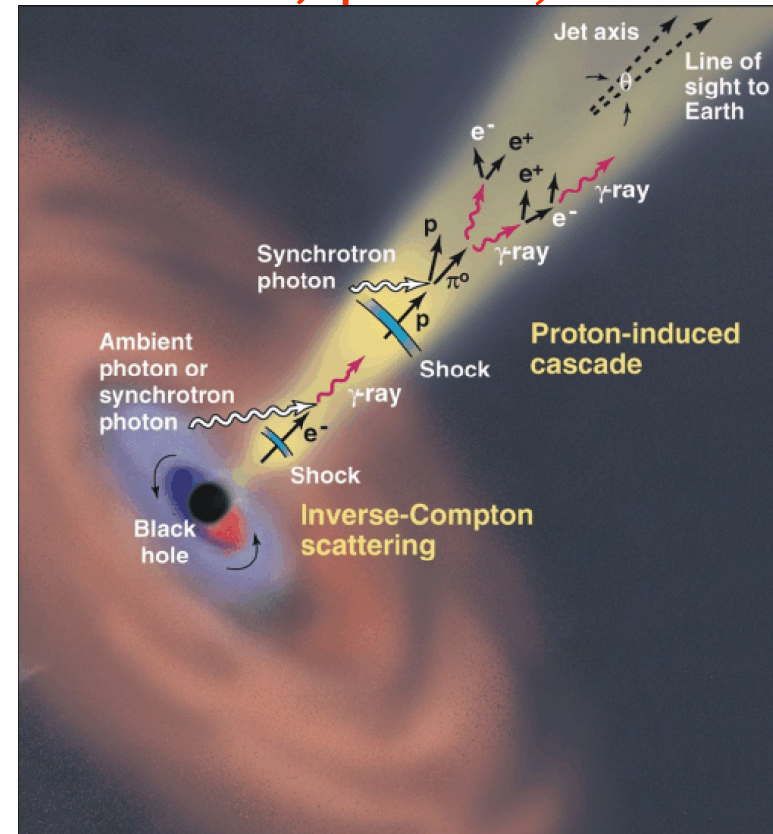


## Active Galactic Nuclei (continued, part 2)

The highly anisotropic nature of AGN is thought to explain the wide variety of AGN known. Quasars are now thought to be those AGN which have jets closely aligned with our line of sight. The emission from quasars is dominated at most wavelengths by emission associated with the jet. These objects can emit photons from radio wavelengths to  $\gamma$ -ray energies above 10 TeV.

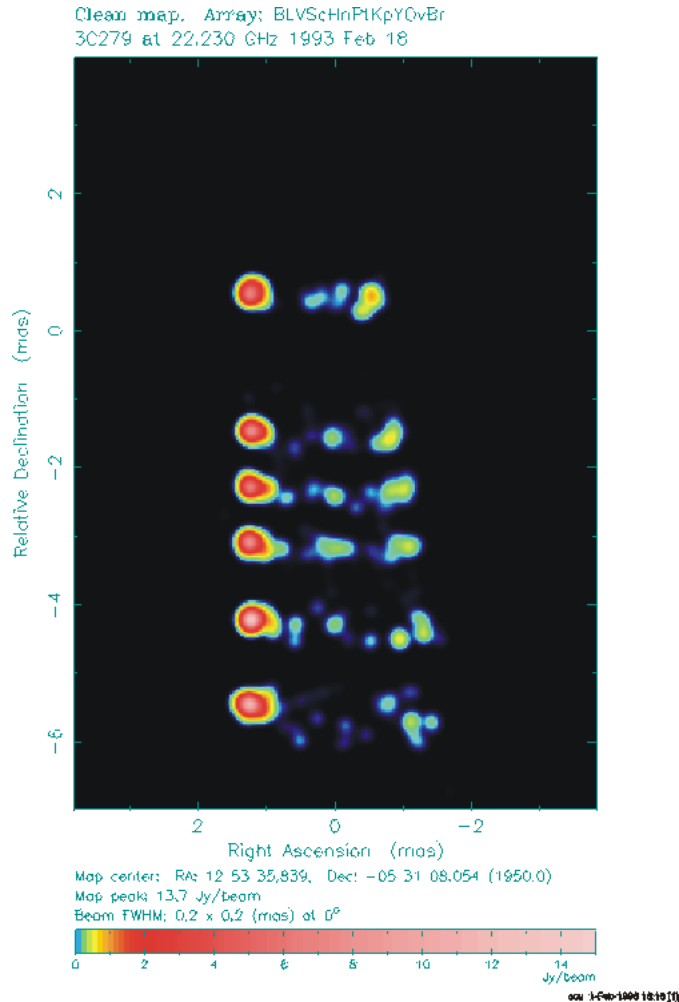
A jet was first observed in the radio galaxy M 87 in 1917 by Heber Curtis using an optical telescope. However, it was not until the 1970's, when observations with large, high resolution radio telescopes, like the Very Large Array in New Mexico, revealed the nature of the "curious straight ray" connected to the nucleus of M87. Jets are present in many, if not all, quasars and can extend millions of light years from the central core of the galaxy.

The artistic rendition above shows two popular models for how the emission from a jet might be produced. It is generally agreed that the emission from radio to optical - X-ray wavelengths is produced by synchrotron emission from relativistic electrons in the jet. The higher energy emission (X-rays to  $\gamma$ -rays) could be produced either by inverse-Compton scattering of electrons and low energy photons or from ultra-relativistic protons (of energies up to  $10^{20}$  eV or more) which initiate particle cascades in the jet. Shocks within the jet could accelerate the particles to the highly relativistic energies needed to produce the  $\gamma$ -rays.





# Superluminal Motion

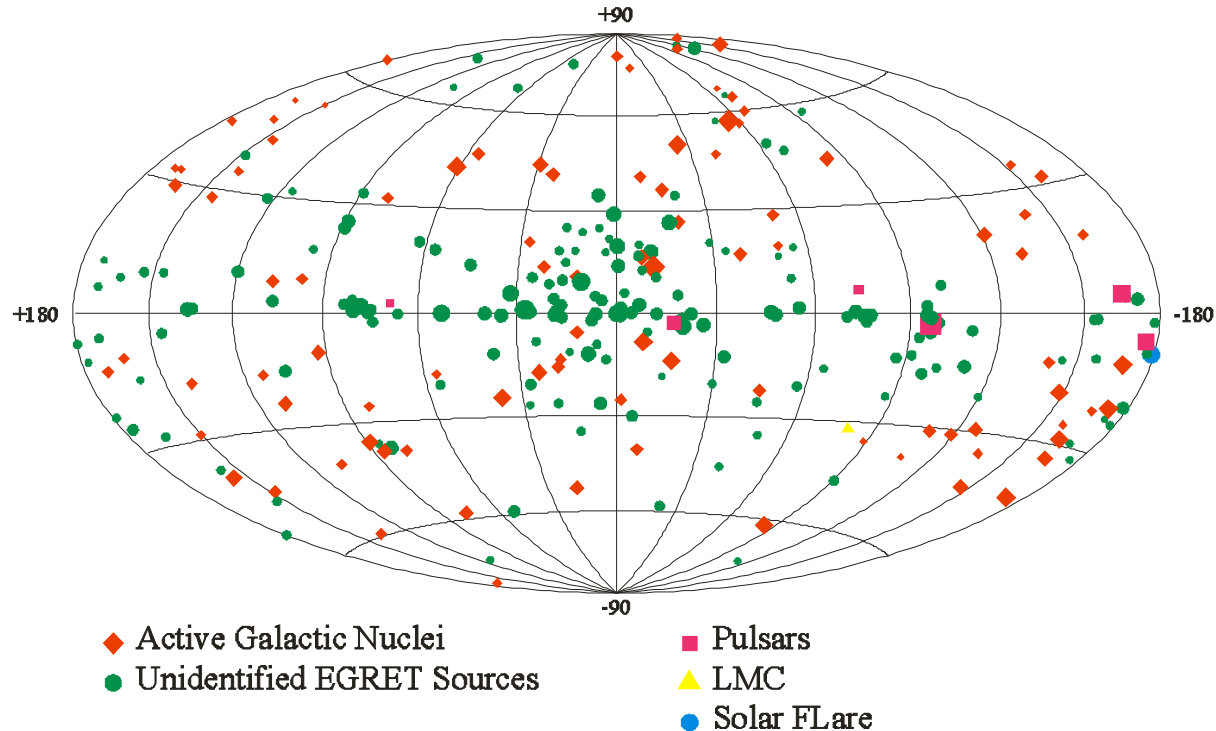


Interferometric radio observations which utilize telescopes spread around the Earth show that the outflows in quasar jets are relativistic. Occasionally, a bright feature (called a knot or blob) is observed to form close to the central core of the quasar and then to move outward with time, as shown in the figure at right. If the redshift of the quasar is known, this motion can be converted into an apparent speed for the knot. In many cases, the knots appear to move at a speed in excess of the speed of light! This effect is called superluminal motion. This speed is actually an illusion, the optical equivalent of the Doppler effect, caused because the blobs which emit the light are moving close to the speed of light in a direction close to our line of sight. This Doppler boosting also increases the apparent luminosity of the object and reduces in the observed time-scale of flux variability.

# $\gamma$ -Rays

## Third EGRET Catalog

$E > 100$  MeV



The first quasar identified as a  $\gamma$ -ray source was 3C273, observed with the COS-B  $\gamma$ -ray satellite that flew between 1975 and 1981. The Energetic Gamma-Ray Experiment Telescope (EGRET), launched as part of the Compton Gamma-Ray Observatory in 1991, increased this number to  $>60$  as shown in the sky map above, indicating that  $\gamma$ -rays play an important role in the emission of many



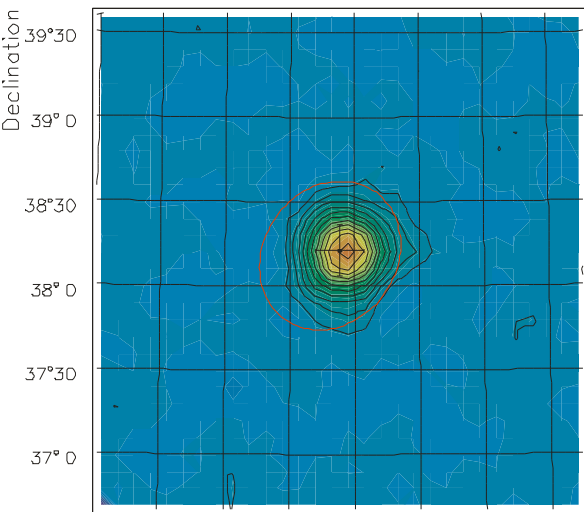
# TeV $\gamma$ -Rays From Blazars

MKN421

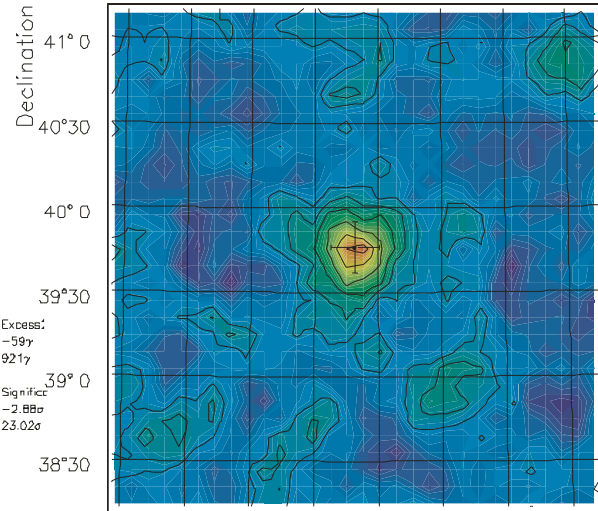
MKN501: Localization

1ES2344+514:  
Localization

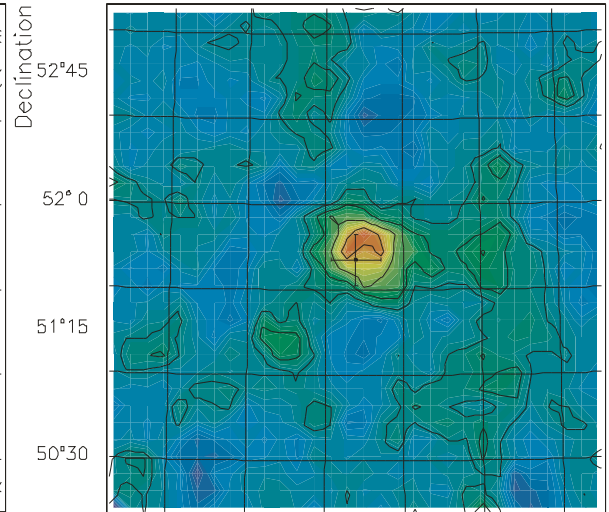
Mkn421 RA: 110427.0, DEC: 381232.0



Right Ascension (J2000.0)



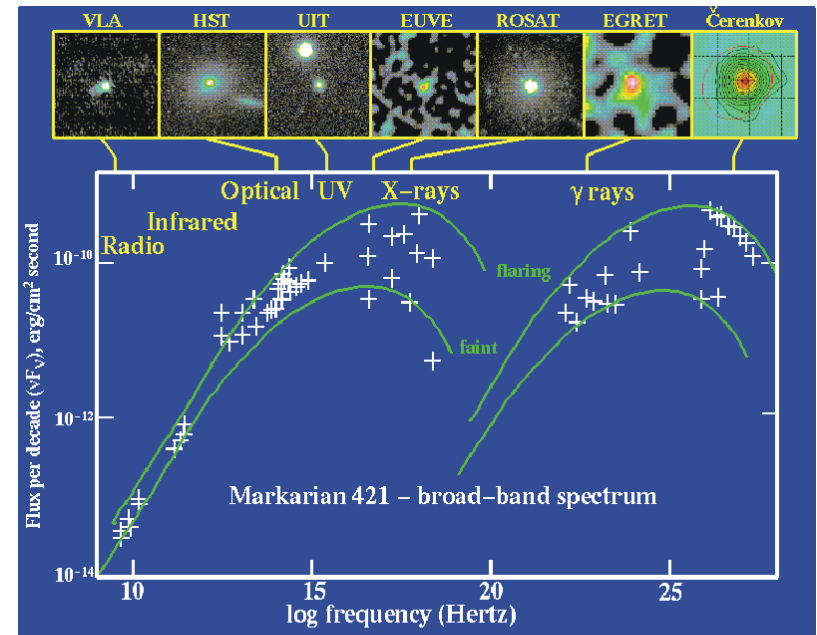
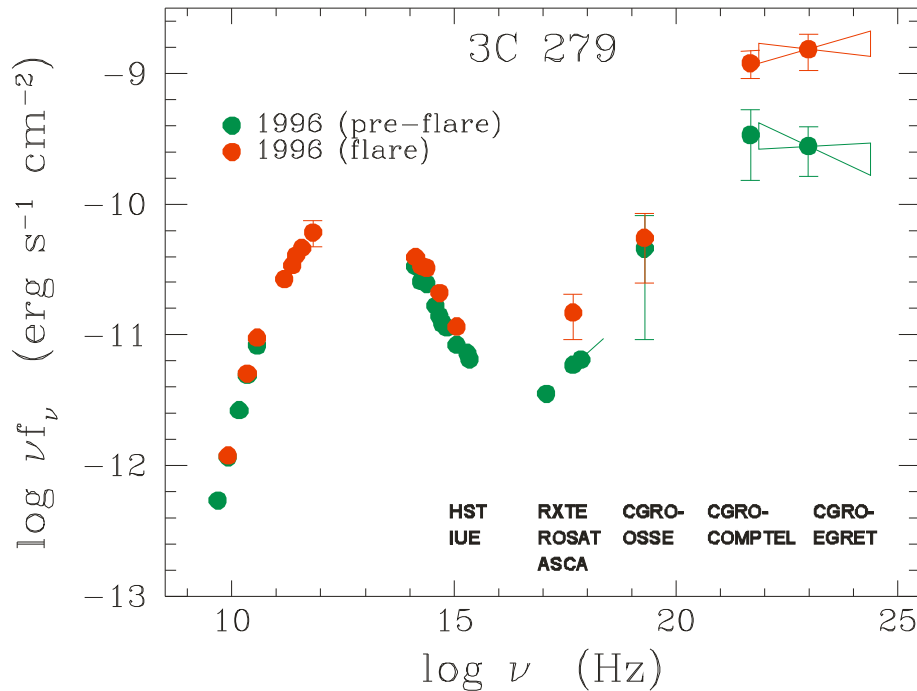
Right Ascension (J1996.2)



Right Ascension (J1996.0)

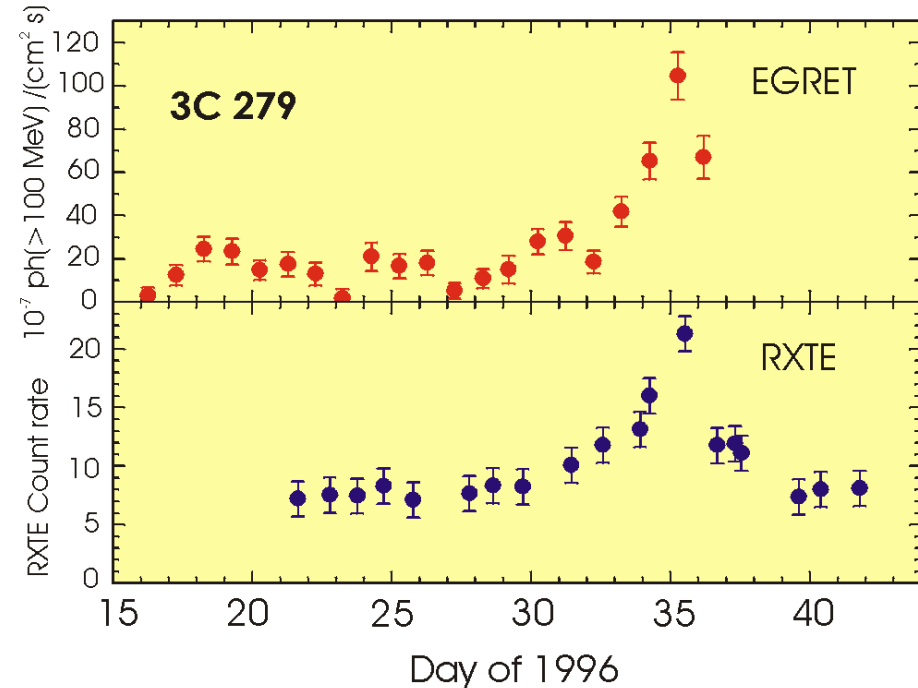
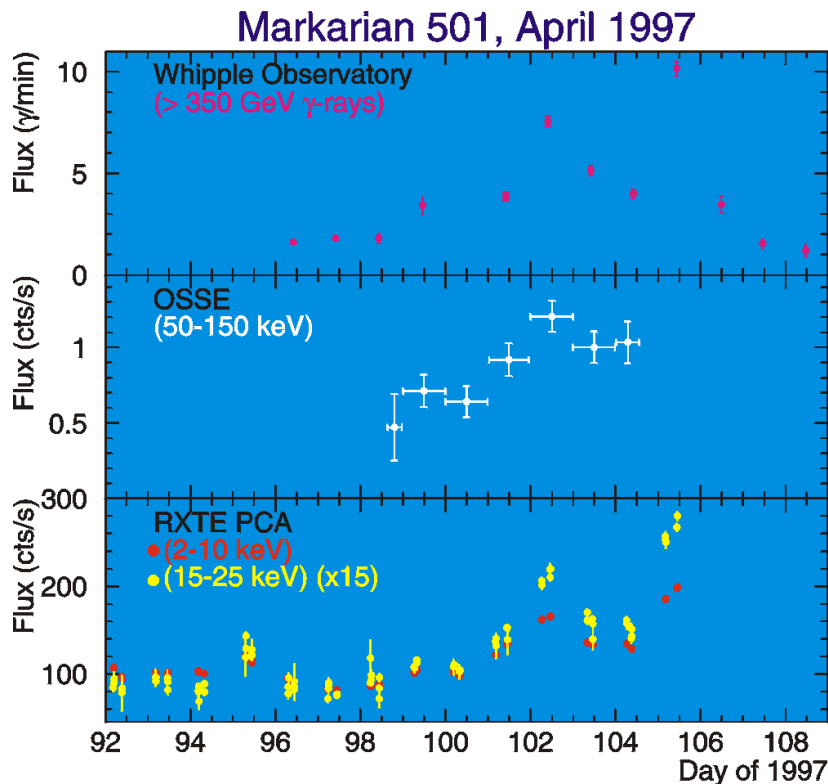
TeV  $\gamma$ -rays were first detected from a quasar, Markarian 421, in 1991 with the ground-based Whipple Observatory  $\gamma$ -ray telescope. Subsequent observations with various telescopes have detected 3-5 more, some images of which are indicated in the figures above. Though small in number, the TeV detections have had an important impact on our understanding of quasars because of the high energies detected (up to 18 TeV at present).

## Power Emitted Per Logarithmic Bandwidth

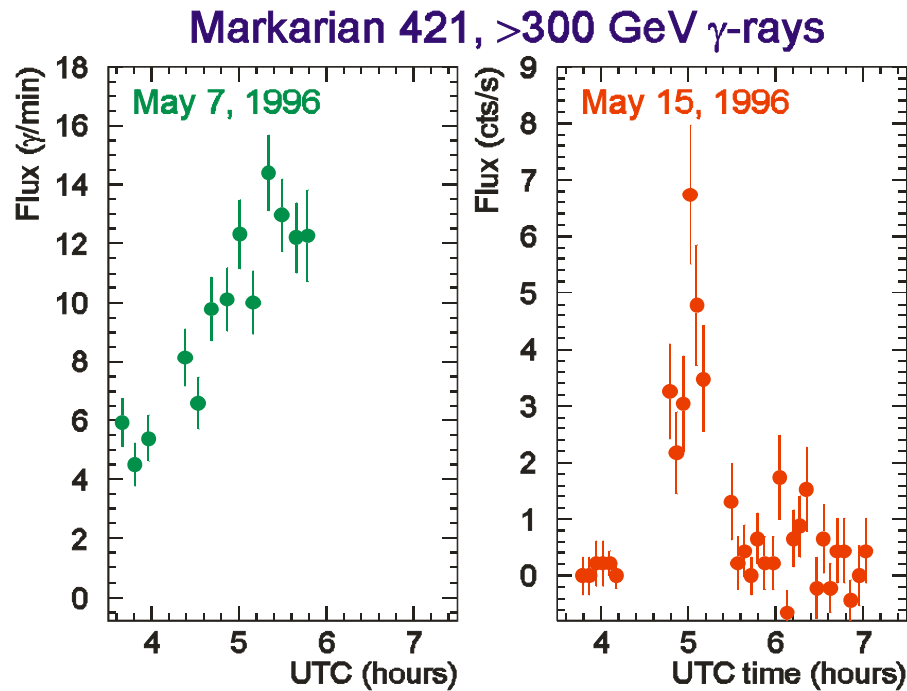


The above plots show the amount of power emitted per logarithmic bandwidth from two quasars, 3C 279 and Markarian 421. These figures show that quasars are very efficient emitters at all wavelengths of the electromagnetic spectrum. Amazingly, as shown in the top figure for 3C 279, the quasars can at times be most efficient at emitting  $\gamma$ -rays. As such, they provide unique laboratories for studying high energy processes

# Multi-Wavelength Variability



Quasars are variable at all wavelengths, so understanding the emission requires that observations be taken contemporaneously with many telescopes operating over a wide wavelength range. These studies are essential to understanding the physics of the central regions of blazars and other AGN, because in general their core regions cannot be resolved with existing interferometers. The time scales, spectral changes, and correlations and delays between variations in different wavebands provide crucial information on the nature and location of the various emission components. The two figures above and to the right show strong correlations between  $\gamma$ -rays and X-rays in the quasars 3C279 and Markarian 501, which imply that both are produced in the same region of the jet. This



**Variability**

Variability is probably the most prominent feature of the emission from quasars. Quasars show flux variations at all wavelengths where they are detected and the magnitude of these variations can exceed factors of 100 and occur on times of less than 1 hour. Due to causality limitations, the rapid variability limits the sizes of the emission regions. The Doppler boosting mentioned earlier alleviates these requirements somewhat, but they still indicate emission arising from regions as small as our solar system.

The two figures above show the fastest variations ever seen at  $\gamma$ -ray energies from a blazar, Markarian 421. The two figures above show the fastest variations ever seen at  $\gamma$ -ray energies from a blazar, Markarian 421. The one observed on May 7 indicates a variability doubling time of 1 hour

# Acknowledgements

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